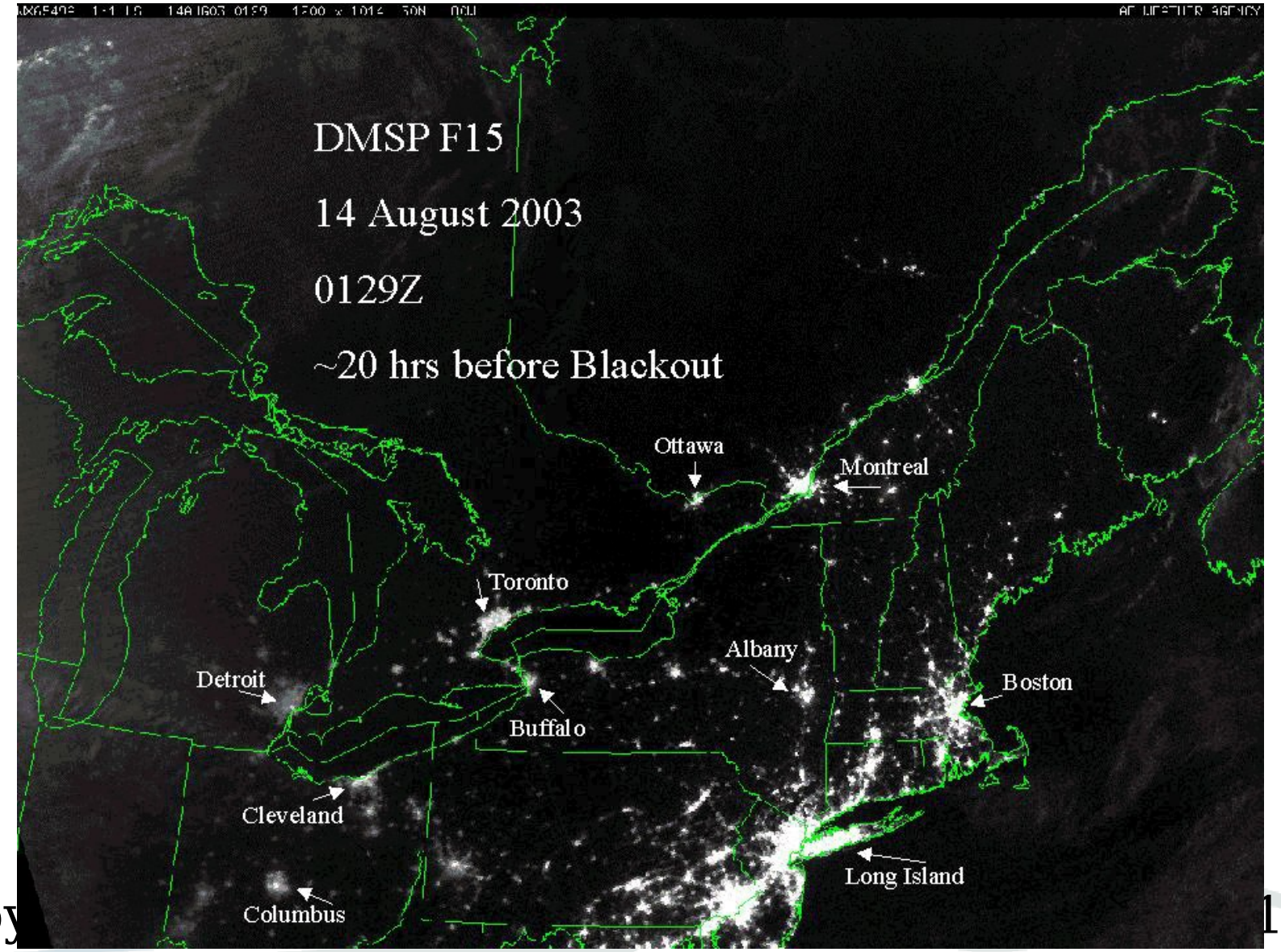
Artificial Evolution to Test and Challenge Complex Control Systems

Icosystem Corp
Cambridge, MA

ONR 334 DIAS Program Review & Workshop
Session: IEP Modeling & Simulation for System Integration & Design
August 10th, 2004

Minor Events Can Trigger Catastrophic Failure…



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Evolutionary/Adaptive Testing

- Identify failure modes in complex systems
- Engineers can only test a small fraction of all possible configurations and damage scenarios
- Possible to find small investments that will dramatically improve robustness? i.e., better design

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Objectives

- **Feasibility of evolutionary testing on a shipboard control system**
- **Modeling ship's firemain system with local valve controls**
- **Evolving *challenges***
  - **Pipe rupture, e.g. from torpedo attack**
  - **Water demand, e.g. ballasting water**

Problem Statement

- **Use *evolutionary computing* to search vast space of possible challenges**
- **Identify particularly problematic combinations of challenges**
- **Study effects of random vs. correlated challenges**

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Evolving challenges

Modeling the ship

USS Arleigh Burke firemain

Firemain Segregation

Condition Zebra

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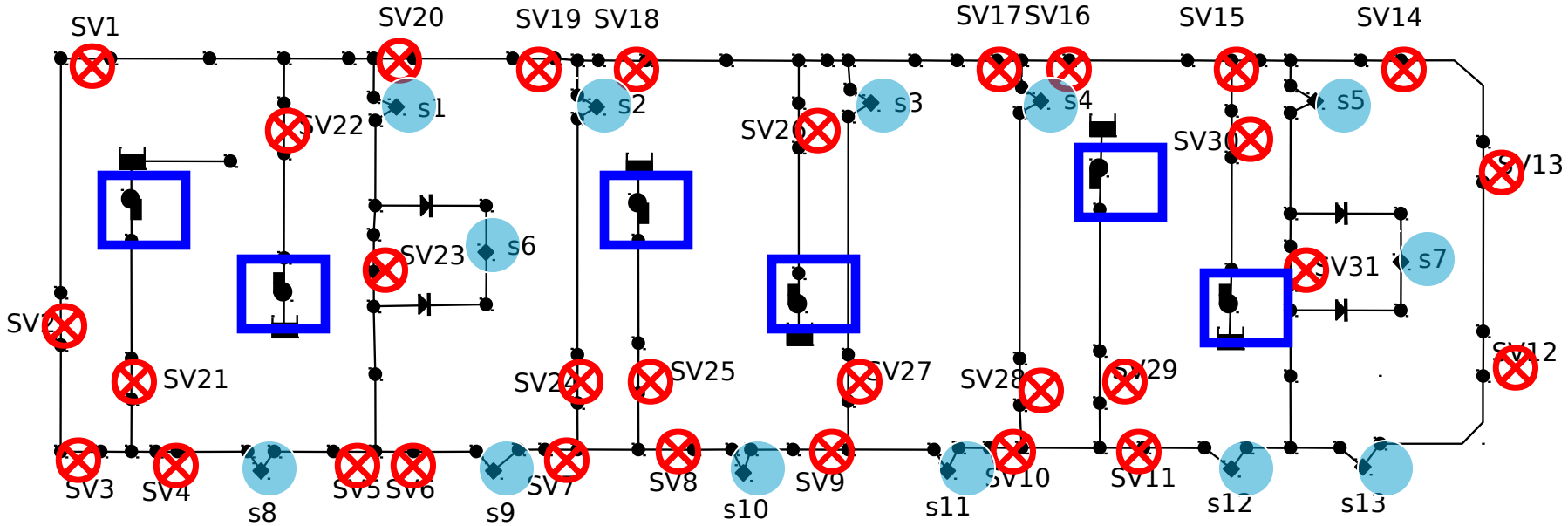
Scale model



Stop valve, local control strategy

Sprinkler valve

Pump, under local control

Challenges:

- **Pipe rupture—e.g. torpedo attack [63pts]**
- **Water demand—e.g. ballasting [49pts]**

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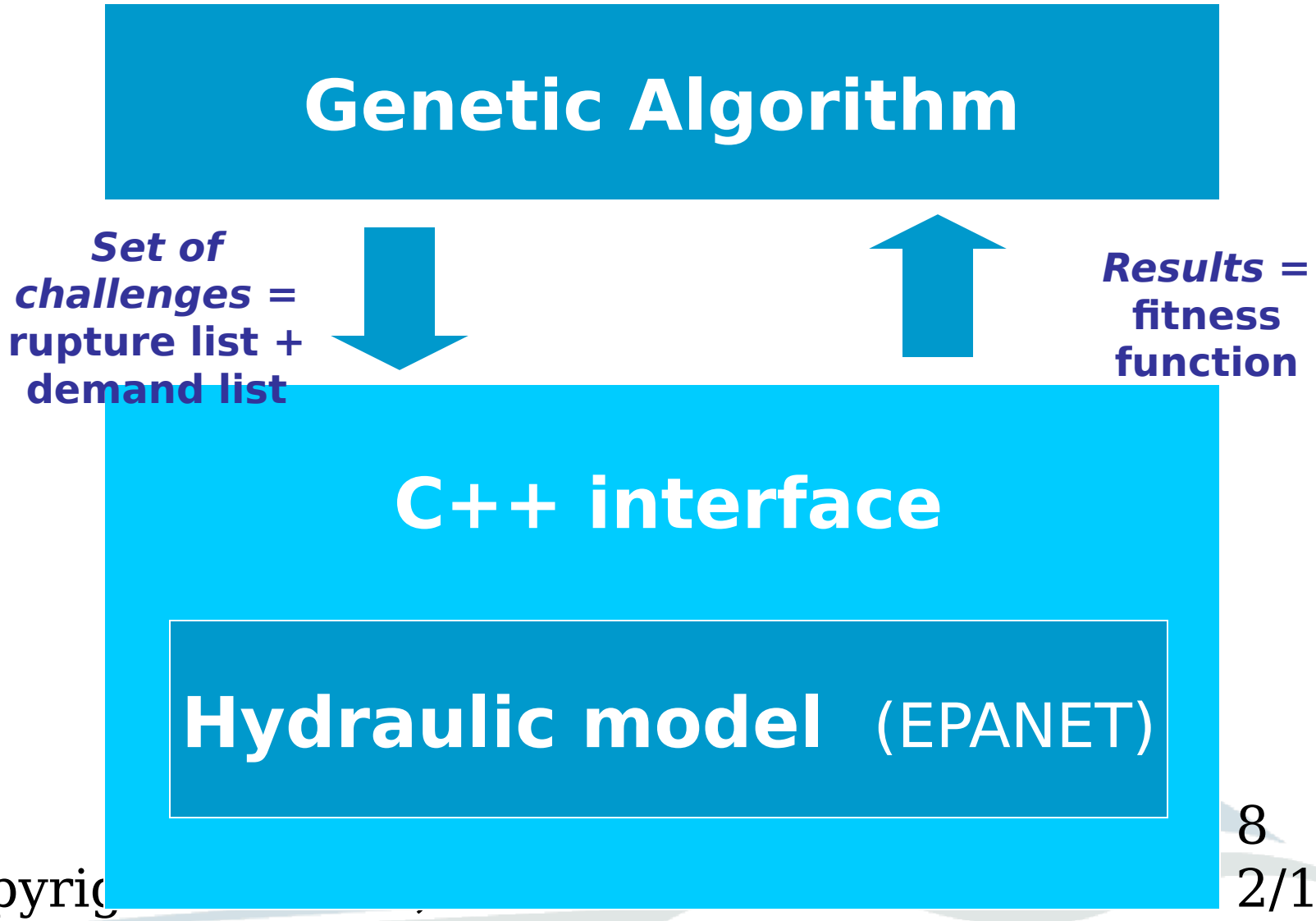
Implementation


Genetic Algorithm
Set of challenges = rupture list + demand list
Results = fitness function
C++ interface
Hydraulic model (EPANET)

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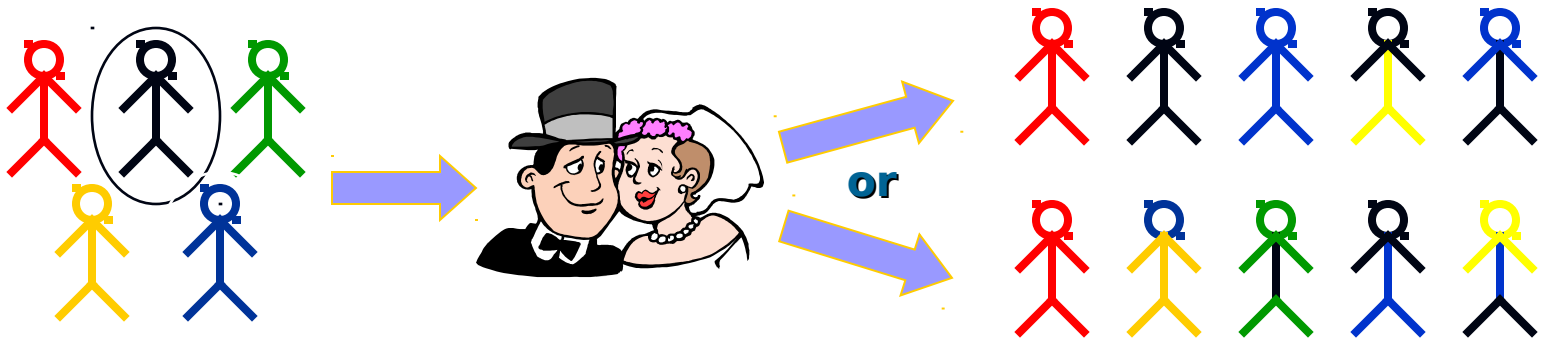
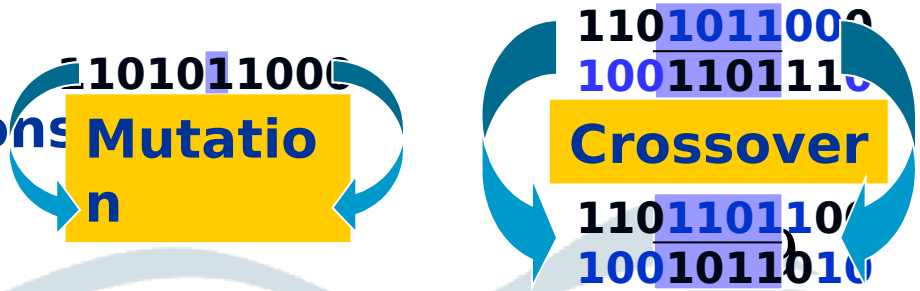
Evolutionary computation

Individuals are represented by genetic string

1101011000…



Two genetic operations



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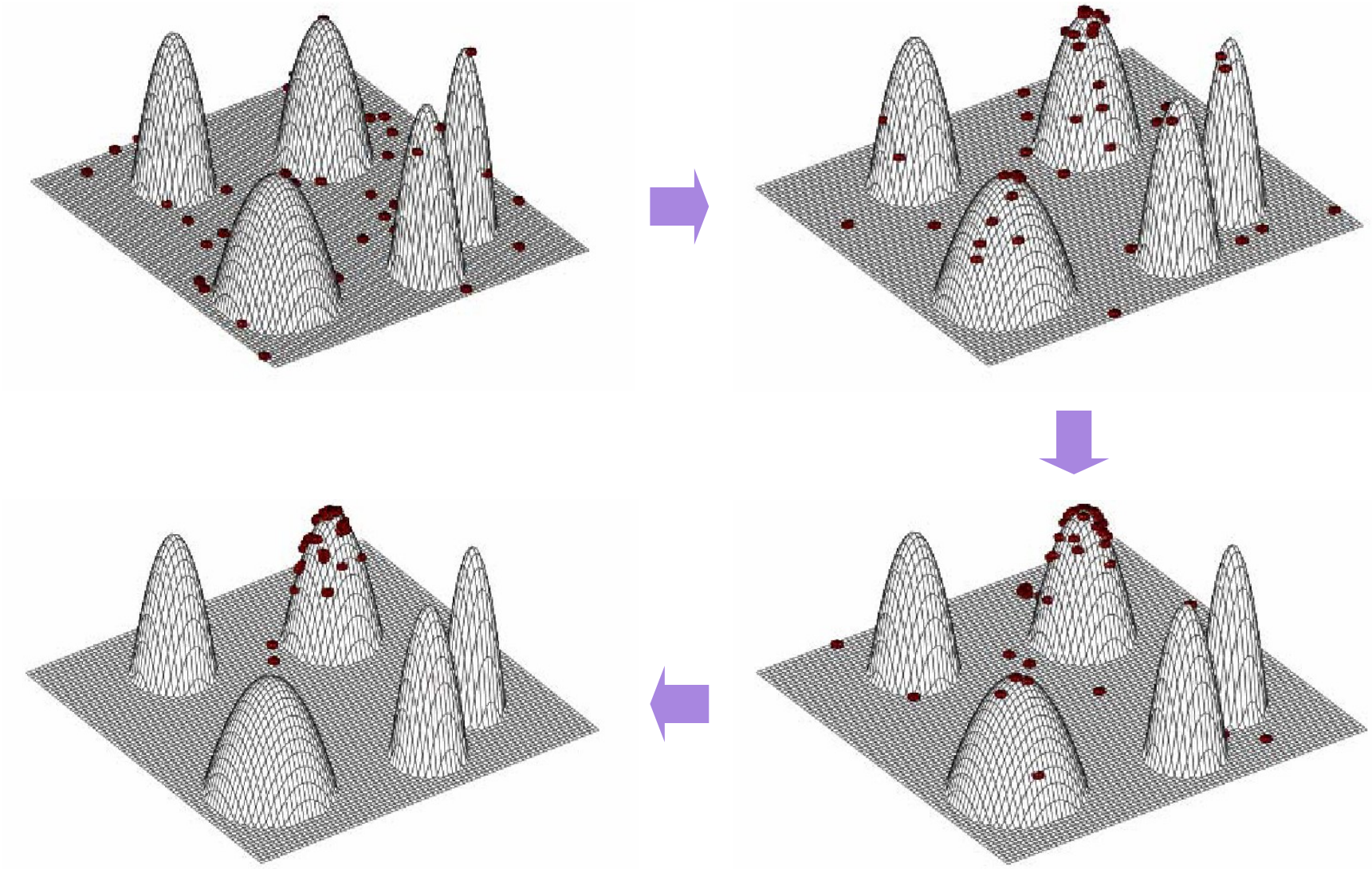
Evolving challenges



From Ken de Jong

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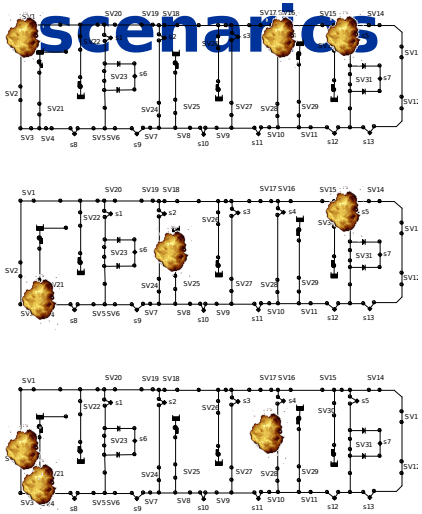
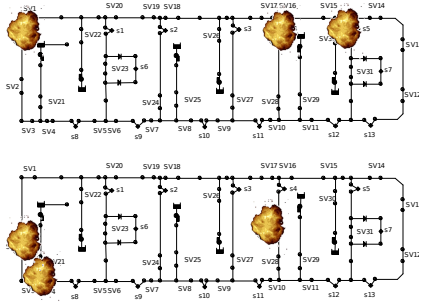
Genetic algorithm

Population of rupture scenarios



Select “fittest”



Create new generation

“breed” from the best

Best = *worst* performance to engineer

Fitness metrics:

- **Deadwater length = sum of length of pipe with no flow**
- **Maximum pump flow = maximum pump speed across six pumps**

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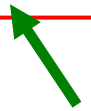
Genotype: Specifies set of challenges

Rchromosome [list of all 63 rupture locations]

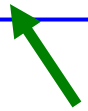
```
0000100000000001000 … 000010000
```



Rupture location 5 [time 0, emitter coefficient 2]

Dchromosome [list of all 49 locations where water can be draw

```
0100000000000000010 … 000010000
```



Draw 500 gallons per minute from location 2

Unconstrained state space = $2^{(63+49)}$

$\approx 10^{34}$

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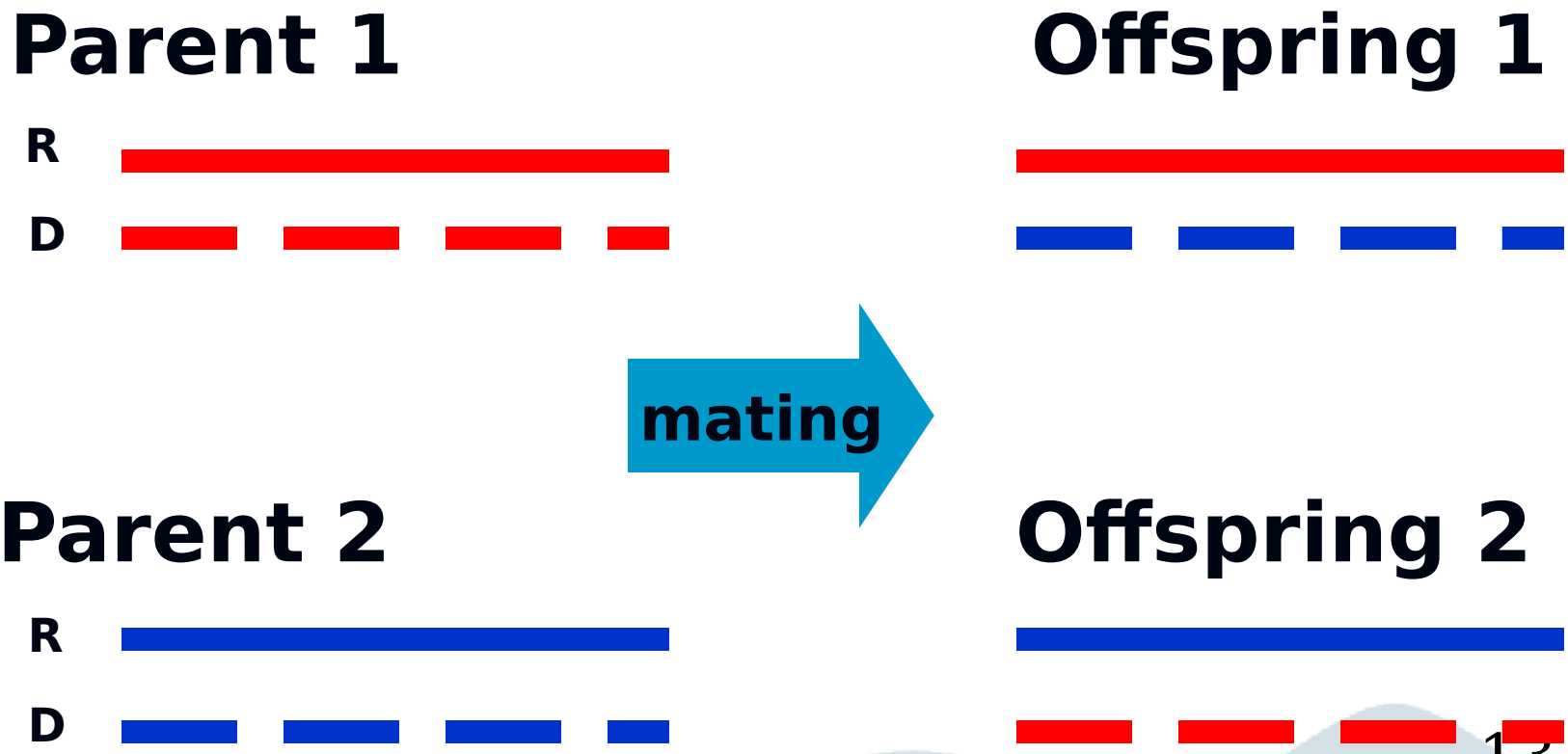
Chromosomal crossover



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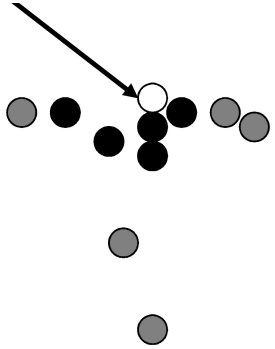
Mutation: rupture nearby pipes instead

Rchromosome

```
0000100000000001000 … 000010000
```



1. Select a pipe ruptu
2. Get list of physical distances to all other rupture locations
3. Take *reciprocals* of distances; sum them; divide each by sum
4. Choose new location probabilistically from this normalized vector

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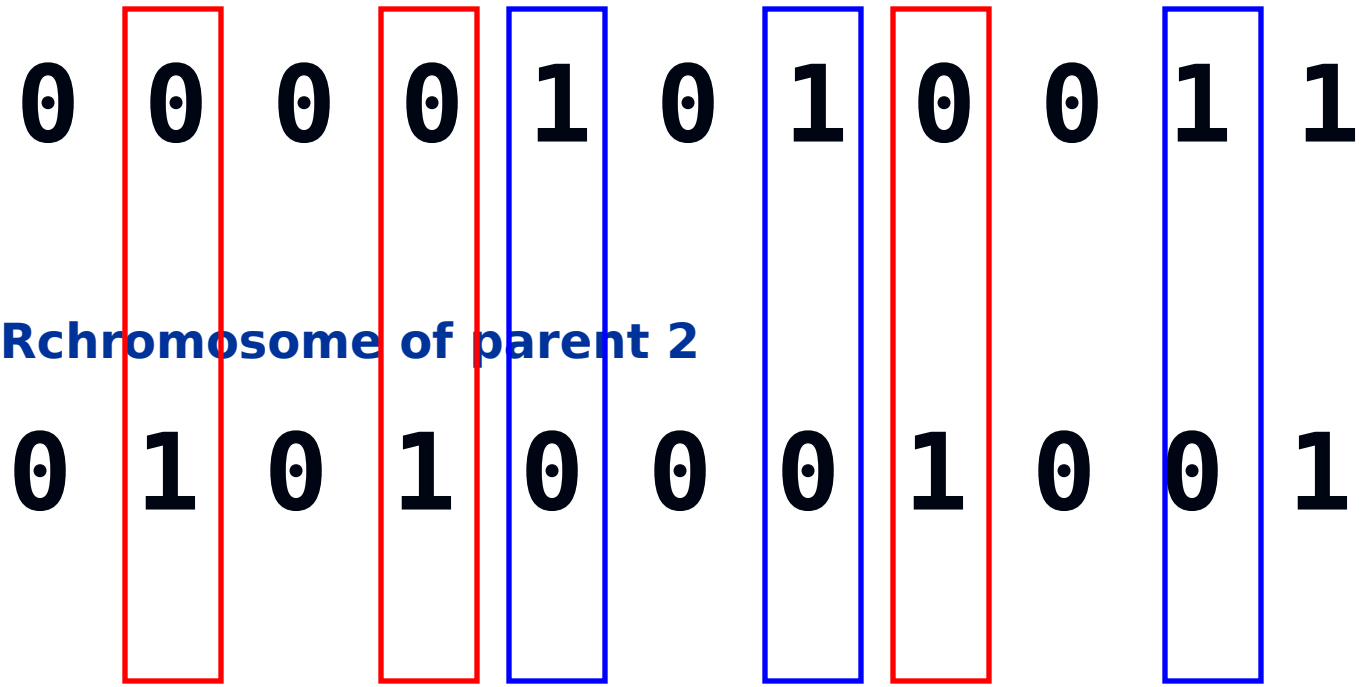
Crossover: while conserving #ruptures

Rchromosome of parent 1



Rchromosome of parent 2

3 pairs available for crossover

1. Pick a red pair and a blue pair at random

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Crossover: while conserving #ruptures

Rchromosome of parent 1

0 0 0 0 1 0 1 0 0 1 1

Rchromosome of parent 2

0 1 0 1 0 0 0 1 0 0 1

3 pairs available for crossover

1. Pick a red pair and a blue pair at random
2. With Probability 0.5 swap them [change 1 → 0 and 0 → 1]

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Crossover: while conserving #ruptures

Rchromosome of parent 1

0 0 0 1 1 0 0 0 0 1 1

Rchromosome of parent 2

0 1 0 0 0 0 1 1 0 0 1

3 pairs available for crossover

1. Pick a red pair and a blue pair at random
2. With Probability 0.5 swap them [change 1 → 0 and 0→1]
3. Do for all pairs (i.e. all remaining reds + their blue partners)

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Parameters

- **Population size** — **50**
- **Elite size** — **10**
- **Number of Ruptures** — **1–3**
- **Number of Demands** — **0–2**
- **Mutation Probability** — **0.5**
- **Meiosis Probability** — **0.5**
- **Crossover Probability** — **0.5**
- **Fitness metric** — **9 to choose from**
  - **“Deadwater” length**
  - **Maximum pump flow**

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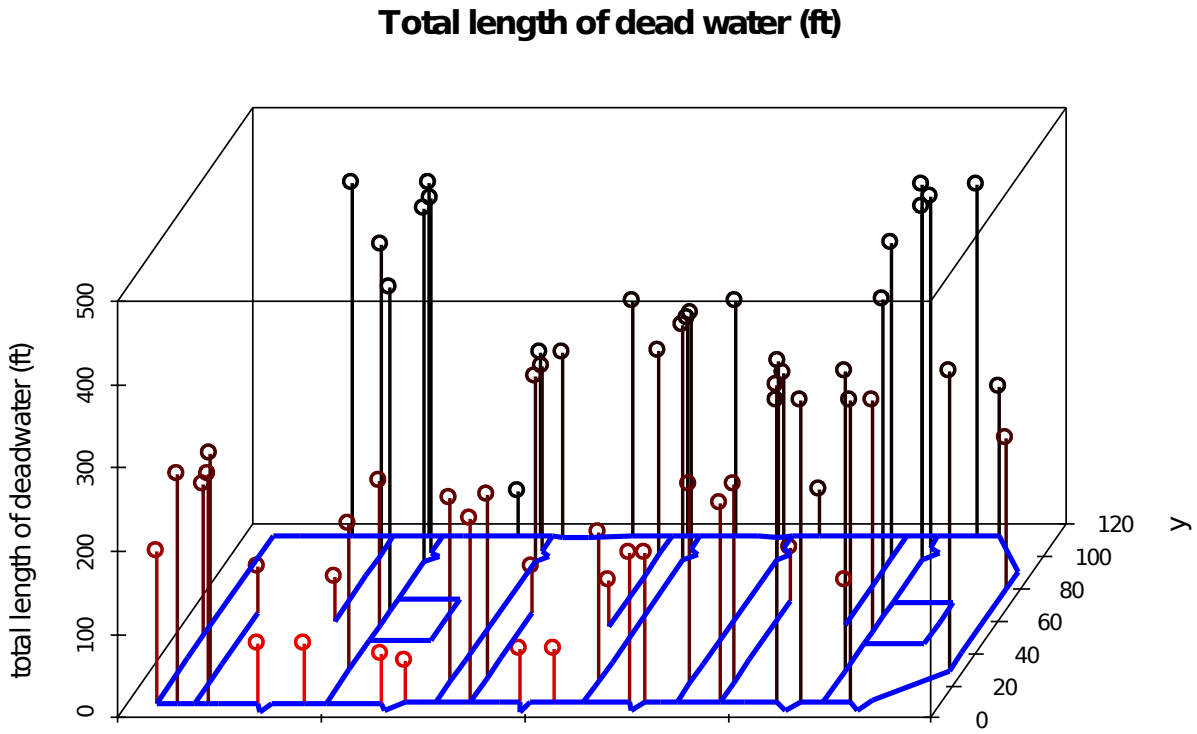
Results:
Finding worst case ruptures

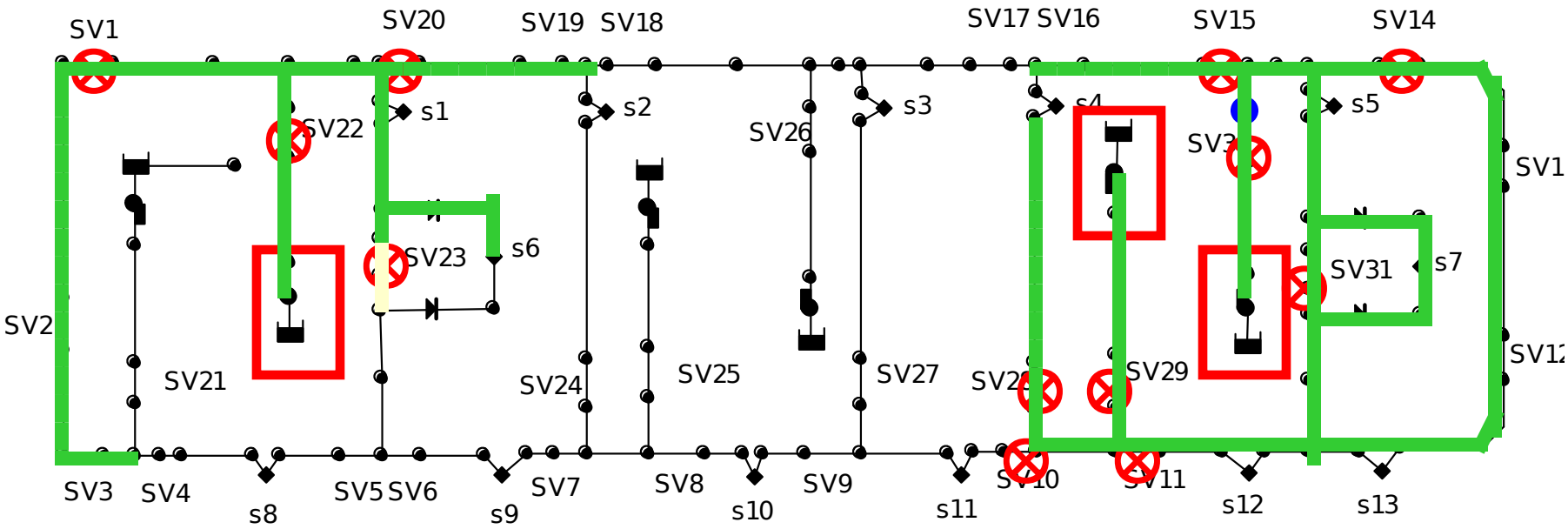
Single Ruptures



Conclusions:

1. **Several “sensitive” areas of the ship, mostly on the port side, fore and aft.**
2. **Four equivalent “worst” locations—GA returns *all* of them simultaneously**

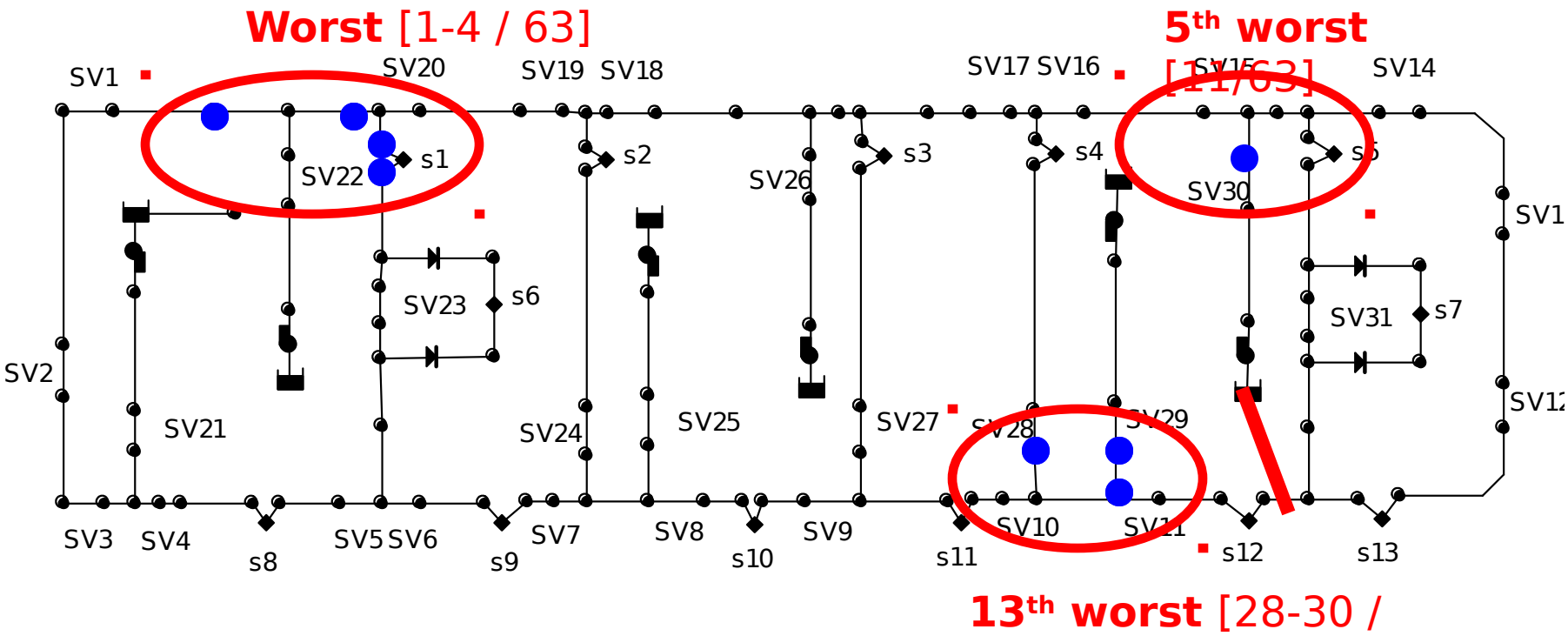
Triple Ruptures



Conclusion:

- **GA found these worst cases < 3min (vs. systematic search: > 3 hrs)**
- **GA took median of 49 generations, i.e. ≈ 1 % of state space**

Triple vs. Single Ruptures



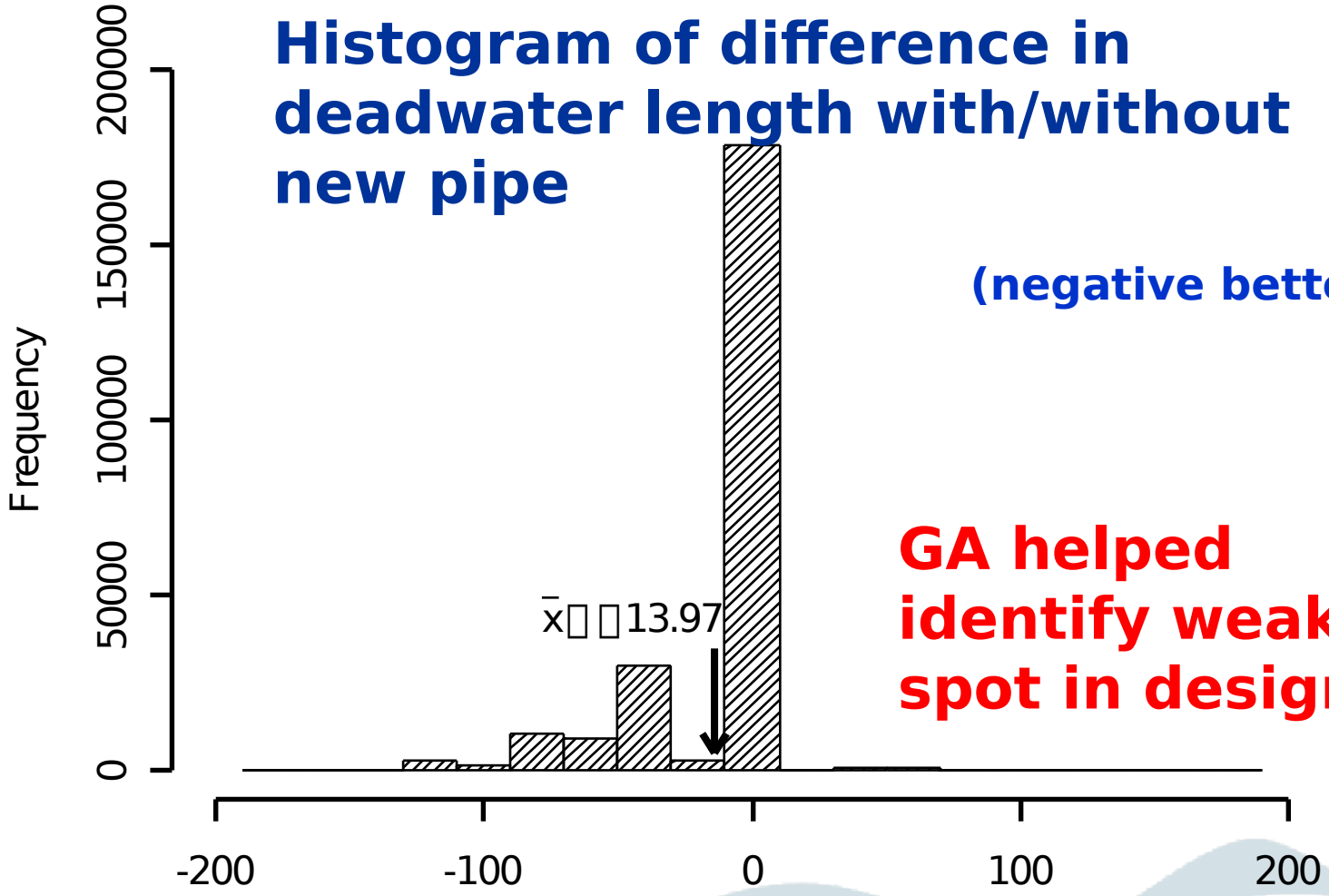
Conclusion:

- **No: worst 3 pt rupture involved “insignificant” locations, low down on list**
- **r56 vulnerable: add in pump → starboard loop riser?**

System redesign

Histogram of difference in deadwater length with/without new pipe

(negative better)



GA helped identify weak spot in design

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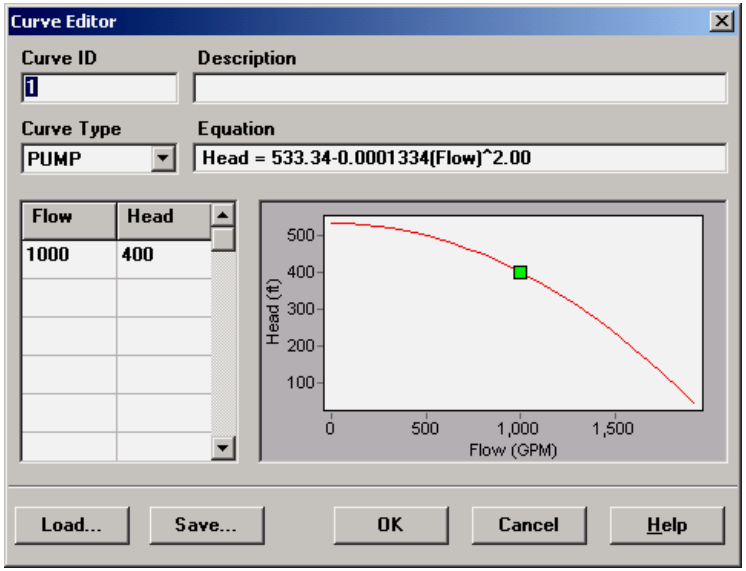
Results:
Threshold search

Threshold search



- **Component constraint**
- **Pump flow rate**
- **Max. safely: 1000 gpm**
- **Threshold 1000**

> **> 1500: dangerous**
> **> 1250: warning**
> **> 1000: overheating**

- **2 ruptures, 2 demands @ 2000 gpm**

- **GA searches and lists all results > threshold**

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Threshold search

- **2 ruptures ⇒ (6-2) × 1500 = 6000 gpm**
- **2 demands 2 × 2000 = 4000 gpm**

Spare capacity: 2000 gpm

- **Set threshold @ 1000 gpm, see what happens…**

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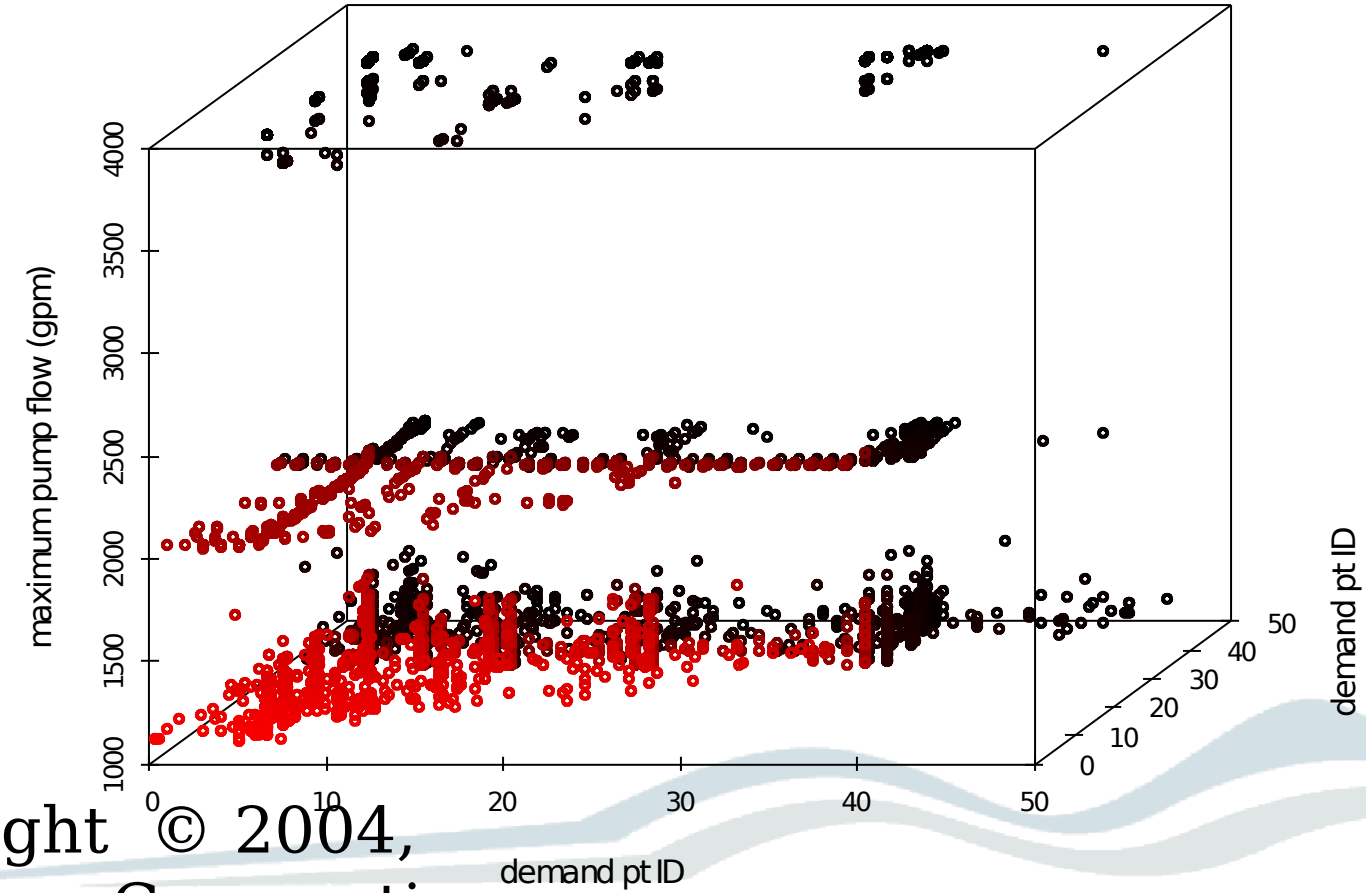
Results

Conclusions:

- **1. Some huge values (4000 gpm)**
- **2. Damage Control (DC) protocol: no-go locations for drawing off water**



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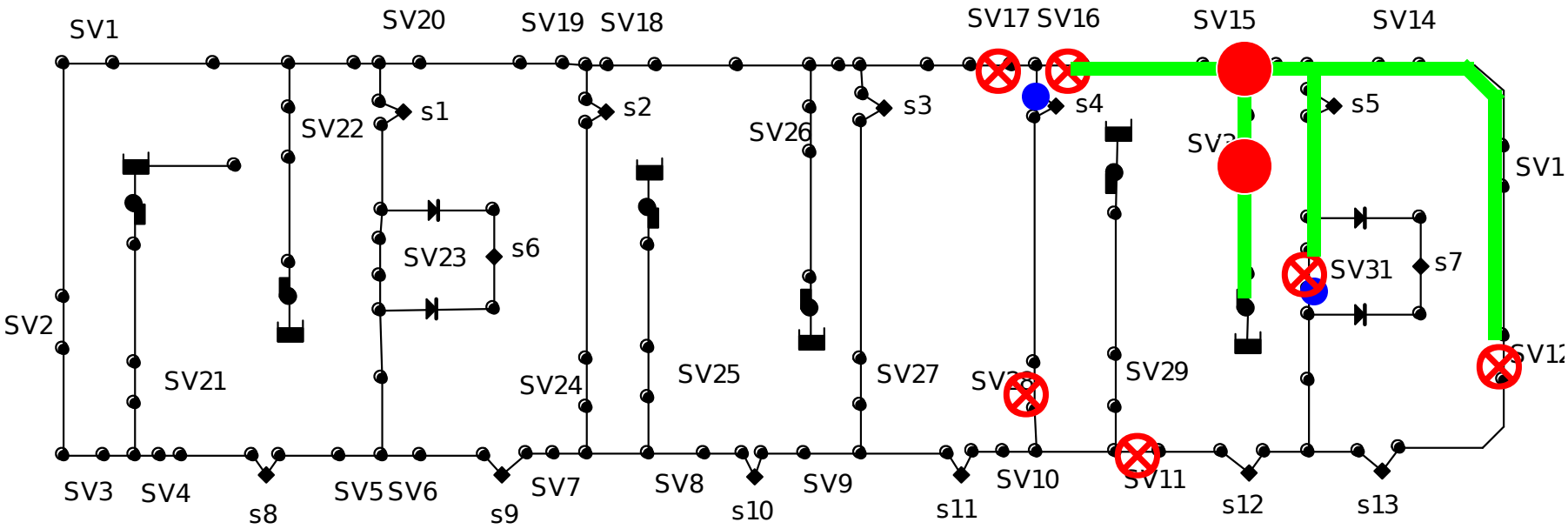
Why was value so high?



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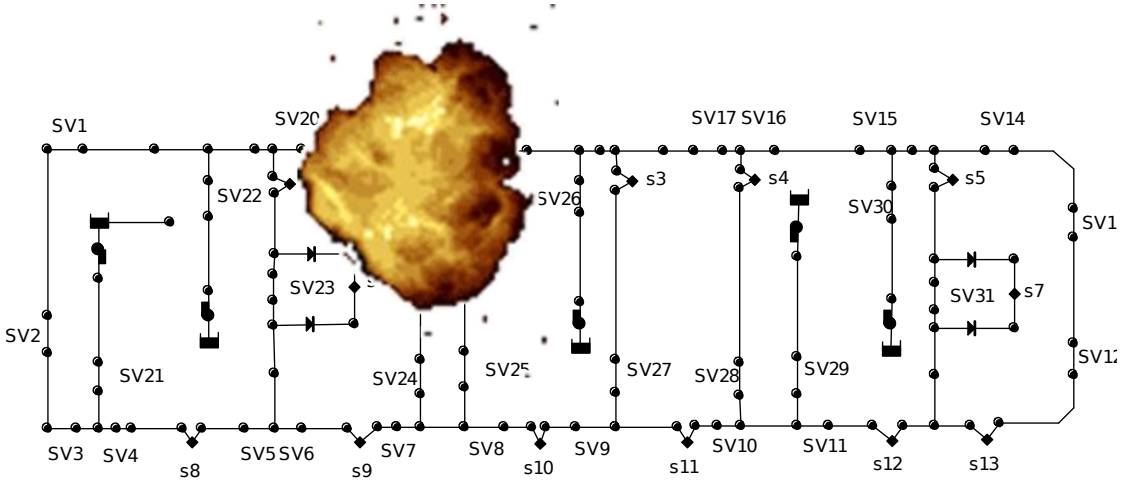
Results:
Correlated damage

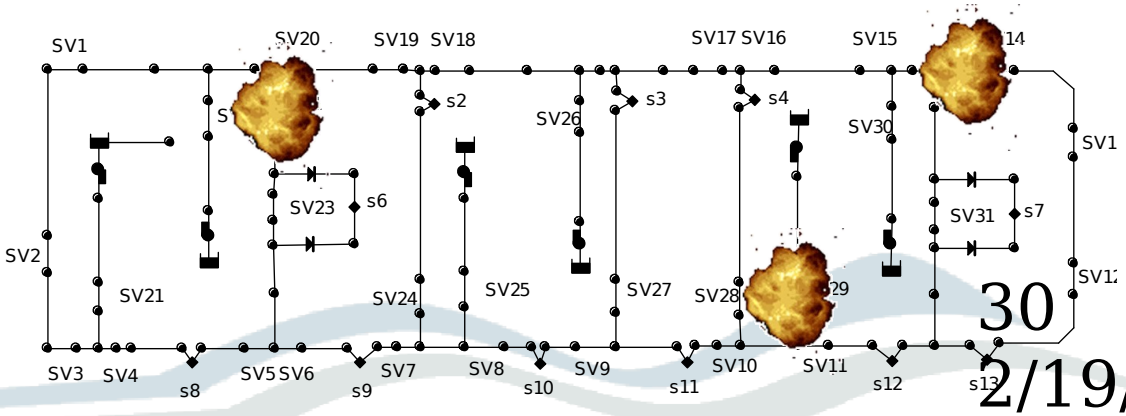
Correlated vs uncorrelated damage

***N* ruptures clustered**

(take N - 1 nearest locations)



***N* ruptures uncorrelated**



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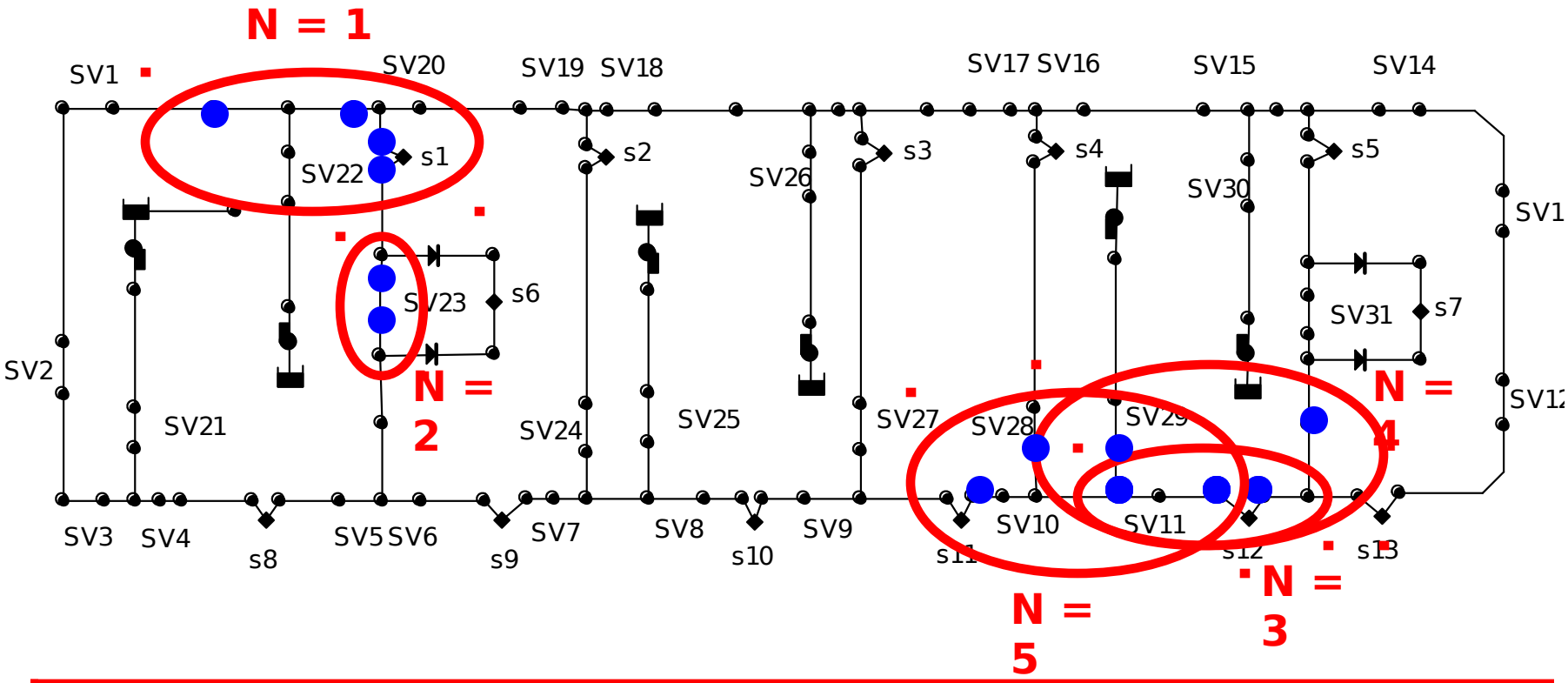
Clustered: deadwater

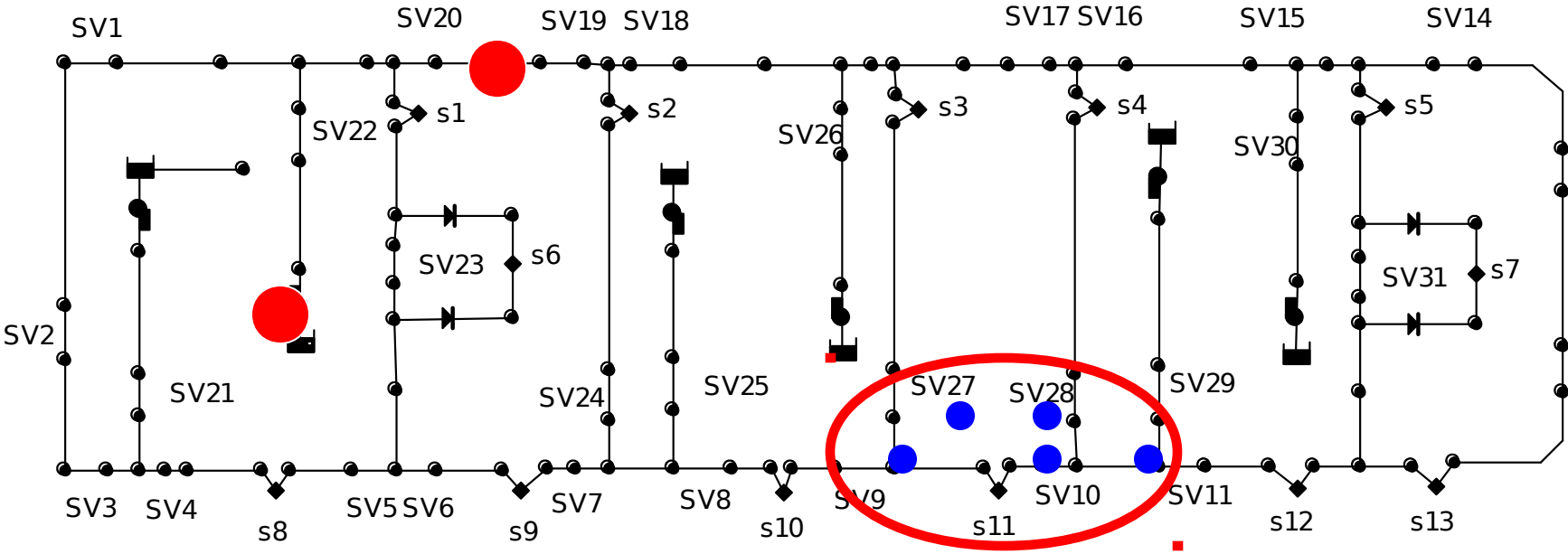


Conclusion:

- **Not a matter of adding onto a cluster in same location—clusters jump**
- **In every case for N > 1, ruptures straddle at least one stop**

Clustered: deadwater

5 clustered ruptures 2 demands



Conclusion:

- **Could be bad news if port-aft ballasting required to prevent list**

Conclusions

- GA proved itself in optimizing worst case scenarios for both correlated and uncorrelated damage
- Some surprising results: e.g. worst 3pt rupture involved an insignificant rupture location halfway down list
- Huge potential for searching for bounds of working conditions [threshold search]
- Tool for design of more robust systems and control strategies (e.g., where to add pipes, where NOT to draw water, ...)

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Future Application

FY 04-05 Collaboration with Fairmount Automation & Syntek Technologies

Implementation of Pilot tool

(1) Realistic system model and damage model (detonation and propagation);

(2) Inclusion of domain expertise into the testing loop;

(3) Development of a tool usable by machinery and control system designers

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Questions?

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